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(54) Title: LASER CUTTING METHOD AND APPARATUS FOR OPTICAL FIBRES OR WAVEGUIDES

(57) Abstract: A cutting method and apparatus are provided to cut a portion of an optical fibre or waveguide with a laser beam. The proposed cutting action takes advantage of the sharp cutting edge of a laser beam generated so as to have a predetermined asymmetric intensity distribution. In operation, a prescribed amount of the beam distribution is impinged on the fibre or waveguide portion and causes the portion to ablate or vaporise so as to effect a cut at the portion in dependence upon the impingement. No translation of the laser beam across the fibre or waveguide is effected during cutting. The proposed cutting action bears definite advantages over conventional cutting techniques and finds utility for many optical fibre or waveguide applications. For example, the proposed cutting action can produce a substantially flat optical fibre or waveguide surface or a lens of enhanced quality at the end of the fibre or waveguide portion.

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LASER CUTTING METHOD AND APPARATUS

FOR OPTICAL FIBRES OR WAVEGUIDES

Field of the Invention

5   This invention relates to a laser cutting method and apparatus and more particularly, but not exclusively, concerns a cutting method and apparatus utilising a laser in optical fibre and optical waveguide applications.

Background of the Invention

The state of the art to which the present invention relates is presented

10   hereinafter in three parts, namely, in relation to: (1) the known technique of mechanical cleaving of optical fibres and optical waveguides, (2) the known techniques for producing lens-shapes on optical fibres, and (3) the known techniques for cutting optical fibres with a laser.

1.   Mechanical Cleaving of Optical Fibres and Waveguides

15   The structure of a typical optical fibre is shown in Figure 1 of the accompanying drawings. In a number of applications in fibre-optic communications it is necessary to couple light either into or out of optical fibres or waveguides.   Sometimes this is accomplished using connectorised fibres where the fibre is attached into a ferrule and then polished to provide an

20   optical quality surface with the end of the fibre lying approximately flush with the end of the ferrule.   However, in other applications, the fibre is not connectorised. In these cases, mechanical cleaving of optical fibres is the accepted technique for preparing the ends of the fibre. This is also the case

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when the ends of the fibre need to be prepared prior to mechanical or fusion

splicing.

Mechanical cleaving involves producing a fiducial stress-raising mark

on the periphery of the fibre (typically with a diamond blade), and then

5   snapping the fibre from the mark. When carried out correctly, this leaves a

high quality, flat surface across the vast majority of the end of the fibre,

including across the crucial core region.

In many applications it is required to minimise the optical reflection

from the end face of the fibre or waveguide back into the fibre or waveguide.

10   This can be achieved by angling the end face of the fibre or waveguide (as

shown in Figure 1) so that the back-reflected light is reflected away from the

core. The greater the angle, the less light is coupled back into the core of the

fibre or waveguide. Typically angles of 6-8° are used which are close to the

limit of what can be obtained with a degree of reliability in mass production.

15   In the interests of increasing the component density in opto-electronic

devices, however, laser sources which emit vertically (normal to the plane of

the chip rather than parallel to it, see Figures 2(a) and (b)) are being

developed.   Coupling the light from these sources into optical fibres or

waveguides presents a challenge to conventional techniques, but can be

20   accomplished using total internal reflection form an end face cleaved at

approximately 45° to the fibre or waveguide axis as shown in Figure 2(b).

Mechanical cleaving has a number of disadvantages and limitations.

Firstly, it produces very sharp edges on the corner of thee cleaved (cut) fibre.

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These are susceptible to handling damage, particularly if the fibre is to be inserted longitudinally into another component.

In some cases these sharp edges are removed in a second process, for example by introducing the tip of the fibre into a flame.

Secondly, the range of angles which mechanical cleaving can achieve is limited. Devices relying on stressing the fibre during the cleave process (either by twisting the fibre or by applying a shearing stress) result in an angle on the cleaved end but in practice this is restricted to <10°. Angles of close to 45° required for coupling light into the fibre or waveguide from vertical emitting lasers by means of a reflection from the end face of the fibre or waveguide (see Figure 2) cannot be achieved. Moreover, the reproducibility of the cleave angle is less than is called for in many applications, with ±0.5° being difficult to maintain in mass production whereas ±0.2° is often desired.

Thirdly, as mechanical cleavers depend for their operation on precision moving parts including a very sharp blade, they are prone to wear and misalignment, requiring more readjustment and refurbishment than is ideal for mass production.

Fourthly, the mechanical cleave process, involving such precise and intimate contact between the cleaver and the fibre, is inherently difficult to automate. Such a non-automated process requires considerable manpower resources to produce large volumes, and the yield is dependent on operator skill which leads to product variability.

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Fifthly, the size of the hardware involved in the mechanical cleave means that is not possible to cleave very close to other objects. For example, cleaving cannot generally be carried out closer than about 10mm from a ferrule or connector.

5   Further, mechanical cleaving cannot produce the very tight fibre-to-fibre cut length tolerances required of ribbon fibres, where tolerances of $\pm 2\mu m$ or less are required.

2.   Producing Lens-Shapes on Optical Fibres and Waveguides

Increasing data traffic is placing ever greater demands on the

10   performance of optical communications systems. These include capacity, bandwidth and distance between amplifiers or repeaters.

Crucial to meeting the above objectives is to maximise the efficiency of the whole system. This not only reduces the power consumed and/or allows the use of fewer amplifier/repeaters, but results in less waste heat and

15   hence thermal loading of the components. This reduces the thermal management hardware needed, permits tighter packaging of components, and allows the active devices to be operated at lower temperatures, which has a significant beneficial effect on component lifetimes.

One significant source of inefficiency in a pig-tailed transmitter or

20   pump laser is the coupling of the emitted laser power into the attached fibre. The problem here is to couple the divergent optical output from the laser diode, which will have an effective source size of a few microns and usually different beam divergences in the two orthogonal dimensions, into the

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(usually) circularly symmetric core of an optical fibre or waveguide which, for a single mode fibre or waveguide, will be between 3 and 20μm in diameter, or may be up to 62μm or more for multi-mode fibre or waveguides.

5   The optical transfer from the source to the fibre or waveguide is often accomplished using micro-optics inserted between the two components as shown in Figure 2(c). The production and alignment, assembly and subsequent permanent fixturing of these discrete components is problematic. For reasons of availability and ease of alignment, the lenses are often spherical and symmetric, although it is clear that aspheric, asymmetric lenses

10   would provide superior performance.

Producing a lens-shape directly on the end of the optical fibre or waveguide can reduce the alignment difficulties by avoiding the need for the additional (aligned) component. Various techniques for manufacturing such a lens have been described, including etching, selective etching (where the

15   cladding is selectively removed and the core then etched), grinding, pulling the fibre in the presence of a heat source (usually an electric arc) and laser micro-machining.

The laser route has a number of advantages in terms of speed, flexibility and reproducibility.

20   The use of a CO_2 laser to machine lens shapes on optical fibres by means of a micro-lathe approach has been described in a number of patents (for example, see US 4,710,605, EP 0 391 598 B, EP 0 558 230 B). In these patents, the laser is focused to a spot, which is then scanned across the end of

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the rotating fibre, providing a machining approach which is analogous to a conventional mechanical lathe.

This approach introduces a significant heat input into the fibre. This results in a re-flow of material which is influenced by surface tension effects.

5   The net result is a smoothing of fine detail and a tendency toward smoothly curved and ultimately near-spherical surfaces. For the purposes of these patents, this is a largely helpful phenomenon when producing relatively gently curved lenses with tip radii (assuming the spherical case) in excess of 10µm. However, production of radii less than 10µm is problematic with the

10   micro-lathe technique.

Moreover, in practice the technique is relatively slow (of order 15s per fibre), and tends to "flare" the fibre, causing the fibre outside diameter (OD) to locally increase beyond the nominal 125µm, as shown in Figure 3(a). This is a severe disadvantage if it is wished to passively align the fibre to an active

15   device (say a laser source) by laying the fibre in a v-groove (Figure 3(b)). In such an application, the tolerance on alignment is typically of order 0.3µm, and so even 1µm levels of flare have a significant detrimental effect.

In addition, the significant thermal input in the process described above can result in diffusion of the dopant which defines the core and hence

20   the active region of the fibre (see Figure 4). This core diffusion can have a deleterious effect on the optical performance of the lens.

Furthermore, the significant thermal input can cause severe problems when machining polarisation maintaining (PM) fibre, which typically have

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asymmetrically distributed inserts of a different or doped material within the fibre to provide stress directions and hence the PM axis. This different material will generally have different thermal properties to the surrounding quartz, in particular it will melt and re-solidify at a different (usually lower)

5   temperature. If the laser lensing process produces a significant melt region, as the micro-lathe does, the effects of different parts of the end face of the fibre re-solidifying at different times can severely distort the overall surface form.

3.   Cutting of Optical Fibres with a Laser

The use of lasers to cut optical fibres has also been described.

10   US 5,421,928 (Siecor Corporation) describes a method in which a focussed laser beam is used to cut excess optical fibre protruding from a ferrule prior to polishing, and EP 0 987 570 A (The Whitaker Corporation) describes a process in which a focussed laser beam is translated across a fibre in order progressively to cut through the fibre (a similar technique is disclosed in

15   US 4 932 989).

Objects and Summary of the Invention

The principal object of the present invention is to overcome or at least substantially reduce some at least of the abovementioned problems.

It is an object of the present invention also to provide an improved

20   laser cutting method which is precise, reliable and reproducible during operation for optical fibre and optical waveguide applications.

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It is also an object of the present invention to provide a simple, robust, and cost-effective route to laser machining fibres employing no moving parts and the smallest laser size practicable.

It is another object of the present invention also to provide an
5   improved laser cutting method which is capable of achieving one or more of a reduction in the volume of molten fibre or waveguide material produced, a low interaction time to substantially prevent thermal conduction/diffusion effects, a low fibre or waveguide end flare, a sharp cutting action and a high local laser intensity at the fibre portion or waveguide to be cut.

10   Further, it is another object of the present invention also to provide an improved method of forming a lens on optical fibre or waveguide which is precise and reliable, and which is capable of achieving in a controllable manner one or more of: low thermal conduction/diffusion effects, a low optical absorption depth of laser in the fibre or waveguide material, a sharply
15   curved lens-shape (for example, with a tight lens tip radius), a fast processing of the fibre or waveguide material, a low fibre or waveguide end flare and a low core diffusion.

In broad terms, the present invention in one of its aspects resides in the concept of taking advantage of the sharp cutting edge of a predetermined laser
20   beam intensity profile to provide a controllable ablation and vaporisation of selected optical fibre or waveguide material, such ablation and vaporisation enabling a cutting action of the type which meets the aforementioned objects to be effected.

Therefore, according to a first aspect of the present invention there is

provided a method of cutting a portion of an optical fibre or waveguide with a

stationary laser beam, the method comprising: generating a beam of laser light

with a predetermined intensity distribution which exceeds, in one dimension,

5   the width of the fibre or waveguide, aligning said beam distribution in relation

to a portion of an optical fibre or waveguide to permit an amount of said beam

exceeding a predetermined level of intensity to impinge on said portion to be

cut; and cutting said portion in dependence upon the impingement of said

beam on said portion so as to form a substantially flat optical fibre or

10   waveguide surface of enhanced quality.

According to a second aspect of the present invention, there is

provided a method of forming a lens at an end portion of an optical fibre or

waveguide with a stationary laser beam, the method comprising: generating a

beam of laser light with a predetermined intensity distribution; aligning said

15   beam distribution in relation to an end portion of an optical fibre or

waveguide to permit an amount of said beam exceeding a predetermined level

of intensity to impinge on said end portion; and cutting said end portion in

dependence upon the impingement of said beam on said end portion so as to

form a lens of enhanced optical quality at said end portion.

20   The present invention also extends to an apparatus adapted and

arranged to carry out the aforementioned methods, said apparatus comprising:

means for generating a beam of laser light with a predetermined intensity

distribution; means for aligning said beam distribution in relation to a portion

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of an optical fibre or waveguide to permit an amount of said beam exceeding

a predetermined level of intensity to impinge on said portion to be cut; and

means for cutting said portion in dependence upon the impingement of said

beam on said portion so as to form an optical fibre or waveguide surface of

5   enhanced quality, for example a substantially flat optical surface or a lens of

enhanced quality at said portion.

In yet another of its aspects, the present invention resides in the

concept of utilising means other than focussing of the laser beam to provide

the desired sharp cutting edge of a predetermined laser beam intensity profile,

10   enabling a cutting action of the type which meets the aforementioned objects

to be effected.

More particularly according to this aspect of the present invention

there is provided a method of cutting a portion of an optical fibre or

waveguide with a laser beam, the method comprising: generating a beam of

15   laser light with a predetermined intensity distribution other than by focussing,

aligning said beam distribution in relation to a portion of an optical fibre or

waveguide to permit an amount of said beam exceeding a predetermined level

of intensity to impinge on said portion to be cut; and cutting said portion in

dependence upon the impingement of said beam on said portion.

20   This aspect of the present invention also extends to an apparatus

adapted and arranged to carry out the aforementioned method, said apparatus

comprising: means for generating a beam of laser light with a predetermined

intensity distribution other than by focussing; means for aligning said beam

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distribution in relation to a portion of an optical fibre or waveguide to permit

an amount of said beam exceeding a predetermined level of intensity to

impinge on said portion to be cut; and means for cutting said portion in

dependence upon the impingement of said beam on said portion.

5   Conveniently, by utilising means other than focussing of the laser

beam, high intensity laser cutting beam distributions well suited to the cutting

process can be produced. In this connection, the desired generated beam

distribution can be formed by optical interference, imaging or diffraction or

by a combination of such techniques.

10   Having regard to the foregoing, it is to be appreciated that the

method(s) and apparatus of the aforementioned aspects of the invention have

definite advantages over known cutting methods and apparatuses; for

example, the method(s) and apparatus of the invention address the limitations

of the mechanical cleaving (cutting) route.

15   First, and more particularly, the laser cutting action of the invention

produces fibre or waveguide corners which are rounded, and therefore, are

more robust.

           Secondly, the angle of the cut/cleave is governed by simple geometric

considerations between the fibre or waveguide and the cutting laser beam, and

20   so can reach large angles (certainly >45°). Moreover, the cut/cleave angle

reproducibility reflects the reproducibility of this geometry, and can easily

better the ±0.5 degree of reproducibility obtained by mechanical

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cutters/cleavers and indeed the ±0.2 degree of reproducibility specified in some applications.

Thirdly, as the laser route is a non-contact process, there are no blades or mechanically stressed moving parts to wear out or become misaligned.

Fourthly, being non-contact, the laser cutting action of the invention is inherently suited to automated loading and unloading of the fibre or waveguide.

Fifthly, as the cutting is carried out by the laser beam itself and the hardware is remote from the cutting point, the cut can be positioned very close to other components, certainly <1mm.

Sixthly, precision stepping methods exist through which the cutting beam can be stepped from fibre to fibre in a ribbon, giving fibre-to-fibre cut/cleave length variations of <1μm.

Further, the laser cutting of the present invention combines several techniques designed to reduce the undesirable thermal effects of the conventional laser micro-lathe approach. These include, as mentioned previously, minimising the volume of molten material produced, keeping the overall interaction time as short as possible to prevent thermal conduction/diffusion and fibre or waveguide flaring, minimising the optical absorption depth of the laser radiation in the material, using the sharpest feasible "cutting edge" to the laser beam, and employing constructive interference to enhance the local laser intensity, thereby allowing shorter interaction times.

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Advantageously, keeping the quantity of molten material produced during all stages of the interaction to a minimum minimises the undesirable effects of the re-flow of this melted volume. It also minimises the potential transport of the fibre or waveguide dopant from the core region into the

5   cladding (refer to Figure 4). Note also that keeping the laser interaction time to a minimum reduces the thermal conduction from the region which is directly heated by the laser into other parts of the fibre or waveguide, thereby reducing the overall thermal impact.

Further, the lens forming method of the present invention combines

10   several techniques designed to reduce the undesirable thermal effects inherent in the conventional laser micro-lathe approach, allowing, as previously mentioned, the achievement of tighter tip radii, faster processing, minimising fibre flare and core diffusion, and providing the ability to handle polarisation maintaining (PM) fibre. It also avoids the need to move the laser beam into

15   and through the optical fibre as specified in EP 0 391 598 B1 for example.

The above and further features of the invention are set forth with particularity in the appended claims and will be described hereinafter by reference to exemplary embodiments shown in the accompanying drawings.

Brief Description of the Drawings:

20   Figure 1 shows a conventional optical fibre structure with an angled end face to back-reflect light away from the fibre core;

Figure 2 shows three conventional laser-to-optical fibre geometries in which (a) the laser source emits light parallel to the longitudinal axis of the

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fibre, (b) the laser source emits light vertically, normal to the longitudinal axis

of the fibre and (c) the laser source and the fibre are optically coupled by

means of a lens which can be formed directly on the end of the fibre.

Figure 3(a) shows an optical fibre with an increased outside diameter

5   (flare) produced by conventional laser machining treatment and Figure 3(b)

shows the problem of aligning the fibre of Figure 3(a) in a v-shaped groove in

relation to an active source, a laser for example;

Figure 4 shows the fibre of Figure 3 with an unwanted amount of fibre

dopant diffusion from the core region into the cladding resulting from

10   conventional laser cutting of the fibre;

Figure 5 shows, in schematic form, how a cutting action according to

an aspect of the present invention is effected having regard to the relative

alignment between a laser having a predetermined intensity distribution and

the optical fibre region to be cut;

15   Figure 6 shows a conventional laser cutting geometry in which a laser

incision is made in a moving workpiece to produce a slot/cut;

Figure 7(a) shows, schematically, a conventional optics-geometry for

producing a line-focus laser beam with the beam focussed in two different

axial positions in orthogonal axes and Figure 7(b) shows, schematically, a

20   typical optics-geometry of the invention for producing a high intensity

asymmetric line-focus beam at one axial position;

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Figure 8 shows two types of predetermined laser intensity distribution for use in the invention, namely (a) a Gaussian intensity distribution and (b) an Airy-type intensity distribution;

Figure 9 shows two types of mask geometry namely, (a) a rectangular mask and (b) a knife-edge mask for use in the practice of the present invention;

Figures 10(a) and (b) show, schematically, how the local laser beam intensity at the fibre portion to be cut may be enhanced by means of constructive interference between reflected and non-reflected parts of the laser beam;

Figures 11(a) and (b) show, schematically, how a cutting action may be effected in accordance with the present invention by means of a number of successive cutting steps so as to reduce the thermal loading on the fibre to be cut;

Figure 12 shows schematically (a) a rectangular mask geometry for use in the invention and (b) how the mask geometry of (a) is used to produce an increase in the laser beam intensity on the fibre by optical de-magnification;

Figure 13 shows schematically a curved mask geometry for use in the practice of the invention to produce an optical lens structure on the end of the fibre; and

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Figure 14 shows schematically an optical interference geometry for use in the practice of the invention for producing a high local laser beam intensity.

Detailed Description of the Embodiments

5   Figure 5 illustrates, in schematic form, how the cutting action of a method of the invention is effected on a portion of optical fibre or waveguide so as to form an optical fibre or waveguide surface of enhanced quality. More specifically, as shown, the cutting action is affected by impinging an amount 1' of a predetermined laser intensity distribution 1, for example in the form of

10   a Gaussian intensity distribution 1, onto a section 2 (to be cut) of fibre or waveguide material 3 in alignment therewith and ablating or vaporising the fibre or waveguide section 2. Regions 4 of the fibre, adjacent to the fibre section 2, are further subjected to significant levels of heating in dependence upon the impingement, the regions 4 being heated to an appropriately

15   significant level below the fibre or waveguide material's vaporisation point.

Advantageously, the laser cutting procedure of the invention does not involve the production of a mark on the fibre periphery and then mechanical fracture of the fibre as required by the conventional cleaving technique. Note also that in the method of the invention, to reduce/minimise the amount of

20   molten fibre or waveguide region 4 adjacent to the vaporised region 2, the laser beam is absorbed within a thin layer of the fibre or waveguide material 3, and the laser beam profile 1 is arranged to have the sharpest possible cutting "edge".

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In operation of the method of the invention, a CO_2 laser (not shown) is preferably used to generate the laser-beam profile, and advantageously, the CO_2 laser wavelength is changed to 9.4-9.8µm from the more usual 10.6µm to permit the optical absorption in the quartz of the fibre or waveguide to be

5   increased by almost an order of magnitude, resulting in a corresponding decrease in the optical absorption depth.

Turning next to Figure 6, there is shown, for comparison purposes, a conventional laser cutting arrangement in which a cut is performed on a workpiece 10 by using a laser focus to provide a laser "incision" in the

10   workpiece 10. and then moving either the laser focus or the workpiece to translate this incision producing a narrow slot or cut 11, as is shown in Figure 6. This is analogous to the use of a jig-saw in woodworking. This approach can lead, however, to significant thermal input. The present invention is different in principle to this mode of operation, and uses an asymmetric laser

15   beam profile to perform the cutting. This more closely resembles the use of a chisel in the woodworking analogy, and results advantageously in a much more rapid process, leading to a significantly reduced thermal impact.

The most common route to produce an asymmetric laser beam is to incorporate a single cylindrical element 15 in the optical train, often combined

20   with conventional circularly-symmetric (spherical or aspheric) optics 16. This indeed produces a line-focus, however the beam is focused in different axial positions 17, 18 in orthogonal axes as shown in Figure 7(a), leading to a focal intensity not as high as is possible. In order to reach higher intensity a

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cylindrical telescope can be used to expand or contract the laser beam in one

dimension only. As is shown in the embodiment of Figure 7(b), a cylindrical

telescope 20 is combined with a symmetric (spherical or aspheric) focussing

optic 22, and the resulting different numeral aperture in two axes produces a

5   single high intensity line focus 25 ideally suited to laser cutting. Moreover, as

the focus in the two orthogonal axes remains in the same position along the

propagation axis with this arrangement, the intensity in the focal line is

maximised. This yields the highest optical intensity, with the sharpest "edge"

to the beam allowed by free-space Gaussian beam propagation, and allows the

10   shortest possible interaction time to be used which reduces heat conduction,

melt depth and hence reduces flaring and core diffusion.

It is appreciated that the laser cutting of the invention is carried out by

appropriate apparatus using the edge of the incident predetermined laser

power density distribution (see also Figure 5). It is possible to sharpen this

15   edge beyond the limits which Gaussian optics would generally impose by

employing a mask to aperture the beam. This results in an Airy-type power

density distribution 28 having sharper edges (albeit with additional diffraction

structure 28') as shown in one dimension in Figure 8. A Gaussian power

density distribution 27 is also shown in Figure 8 for comparison. Further, the

20   essentially 1-D geometry of the laser cut means that a mask with different

properties in two orthogonal dimensions is most appropriate. Preferably, a

rectangular mask 30 is used as shown in Figure 9. An alternative possibility,

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giving a somewhat modified focal distribution, is to use a single sided mask, for example a knife-edge 31, and that kind of mask is also shown in Figure 9.

To further maximise the local intensity at the fibre or waveguide to be cut, the laser beam may be caused to propagate in such a direction that the

5   partially cleaved (cut) fibre or waveguide reflects the laser beam in such a way that the reflected beam constructively interferes with the non-reflected part of the beam. This effect is illustrated in Figures 10(a) and 10(b). In this way, the local amplitude is doubled (assuming perfect reflection), resulting in a four-fold increase in the local intensity. This requires that the polarisation

10 of the laser beam is parallel to the cut surface (rather than perpendicular) and that the angle of incidence (as measured from the normal top the surface) is less than a critical angle at which a $\pi(180°)$ phase shift occurs on reflection of the beam.

The thermal loading on the fibre or waveguide is advantageously

15 reduced by allowing all but the cutting edge of the laser beam to pass by the fibre or waveguide in use. This is achieved by carrying out the laser cut(s) in accordance with the aforementioned geometry of Figures 10(a) and 10(b), as opposed to the alternative approach shown in Figure 11(b) (top schematic) where the laser beam propagation is shown to be directed into the plane of

20 the paper. The thermal loading on the fibre or waveguide can still further be advantageously reduced by utilising the geometry of Figures 11(a) and 11(b) (bottom schematic). As shown, in these figures, a preliminary laser cut 35, 35' (cut 1) in the normal described way is performed on the fibre or

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waveguide portion 37, 37' to be treated, and thereafter, one or more

subsequent laser cuts 36, 36' are performed, there being slight relative

movement (not shown) between the fibre or waveguide and the laser beam

along the longitudinal axis of the fibre or waveguide between successive cuts.

5   Advantageously, the laser cutting procedure of the invention provides

a high intensity beam with the sharpest possible cutting edge, enabling core

diffusion and fibre flaring to be minimised and producing the most accurate

cut end on the fibre. It is to be appreciated that, whereas with simple

focussing, a Gaussian intensity distribution is the best likely distribution to be

10   achieved, the intensity distribution for use in the present invention may

advantageously be produced by means other than by focussing, for example

by imaging, optical interference or diffraction, or by a combination of such

techniques. Further, it is to be noted that the laser cutting of the invention is

carried out by appropriate apparatus using the cutting edge of the generated

15   laser power density distribution.

Turning next to Figure 12, an advantageous laser intensity distribution

for use in the practice of the present invention may be produced by imaging a

rectangular mask 40 in the image plane by use of a lens 41. As shown, the

arrangement provides optical demagnification of the laser beam in order to

20   increase the local intensity of the laser beam on the fibre to be cut. The

present invention, in this aspect, is therefore different in principle to

conventional modes of operation, and uses a laser beam profile with a sharp

cutting edge, produced by means other than by focussing, to perform the

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cutting. This more closely resembles the use of a chisel in the woodworking

analogy, and results advantageously in a much more rapid process, leading to

a significantly reduced thermal impact.

Figure 13 shows a different mask geometry from that of Figure 12 for

5   use in the present invention. More particularly, as shown, a mask geometry

with a curve-shaped cut 42 is used to provide a varying level of light

transmission such as to permit a particular optical structure such as a lens to

be formed on the end of a fibre. Note that the intensity distribution in the

image (machining) plane is altered by the way in which the object (mask) is

10   illuminated by the laser, which need not be uniform.

Figure 14 shows another optical arrangement of the present invention

in which optical interference is used to produce the high local intensity

desired. As shown in the figure, an optical interference arrangement 50

similar to the so-called Lloyds Mirror in classical optics is used. This is used

15   with a point/slit source 51 and gives rise to a number of parallel fringes 52.

For the purposes of the present invention, it may be used to produce the high

local intensities desired. With correct control over the divergence of the laser

beam (and/or the effective source size), the majority of the photons are

advantageously concentrated into the first fringe, with little energy wasted in

20   the higher order fringes. The resulting intensity pattern is highly concentrated,

yielding the high intensities required.

Other wavefront-splitting interferometers (not shown) are known in

classical optics which produce fringe patterns similar to the Lloyd's mirror

22

arrangement, and which are similarly adapted to optical fibre cutting in accordance with the present invention. These include Fresnel's double mirror arrangement, Young's slits arrangement and Fresnel's Bi-prism arrangement.

In another optical arrangement (not shown) of the present invention

5   the constructive interference of phase-shifted beams is used to produce the required local high intensity. This phenomenon is known in classical optics, but has not been employed in laser machining. Diffraction of the cutting beam using phase masks, zone plates and/or echelle gratings is envisaged so as to effect fibre cutting in accordance with the present invention.

10   Having regard to the foregoing, the laser cutting action proposed by the present invention finds utility for various optical fibre or waveguide applications. In this connection, it permits a selected region of an optical fibre or waveguide to be cut in a controlled fashion enabling various cut angles ($\leq$ to >45 degrees) to be formed in the fibre or waveguide, and as described

15   above, it can be successfully applied to optical fibre or waveguide to form, for example, (1) a substantially flat optical fibre or waveguide surface of enhanced optical quality or (2) a lens of enhanced optical quality at said region. The laser beam during the cutting operation is kept at a stationary position in relation to the fibre or waveguide.

20   Having described the invention by reference to specific embodiment, it is to be well understood that the embodiments are exemplary only and that modifications and variations thereto will occur to those possessed of appropriate skills without departure from the spirit and scope of the present

23

invention as set forth in the appended claims. For example, whereas the described embodiment of the invention uses a Gaussian or Airy-type (non Gaussian) laser intensity distribution, the same or similar technical effect might be obtainable by using a different kind of non-Gaussian laser intensity

5   distribution having a sharp cutting edge. Also, the laser source need not be a CO_2 laser as in the described embodiment and could alternatively be a UV-excimer laser. The invention can also be applied to different optical fibre or waveguide structures where a sharp cutting action is required. It is also to be appreciated that a very wide range of laser intensity distributions might be

10   produced using different kinds of masks having different forms and shapes. Different masks having varying levels of transmission can be used to produce the same or similar technical effect.

CLAIMS:

1.   A method of cutting a portion of an optical fibre or waveguide with a laser beam, the method comprising:

5   generating a beam of laser light having a predetermined intensity distribution which is larger in one dimension than the width of the fibre or waveguide;

aligning said beam distribution in relation to a portion of said optical fibre or waveguide to permit an amount of said beam exceeding a

10   predetermined level of intensity to impinge on said portion to be cut; and

cutting said portion in dependence upon the impingement of said beam on said portion so as to form a substantially flat optical fibre or waveguide surface of enhanced quality.

15   2.   A method of forming a lens at an end portion of an optical fibre or waveguide with a stationary laser beam, the method comprising:

generating a beam of laser light with a predetermined intensity distribution;

aligning said beam distribution in relation to an end portion of an

20   optical fibre or waveguide to permit an amount of said beam exceeding a predetermined level of intensity to impinge on said end portion; and

cutting said end portion in dependence upon the impingement of said

beam on said end portion so as to form a lens of enhanced optical quality at

said end portion.

5   3.   A method as claimed in claim 1 or 2, wherein said cutting is effected

by ablating or vaporising said portion and heating adjacent portions of the

fibre or waveguide.

4.   A method as claimed in claim 1 or claim 2 or claim 3, wherein the

10   generated beam distribution comprises an asymmetric beam.

5.   A method as claimed in claim 4, wherein said asymmetric beam is

formed by use of cylindrical telescope means.

15   6.   A method as claimed in any of the preceding claims, wherein said

predetermined intensity distribution is a Gaussian intensity distribution.

7.   A method as claimed in any of claims 1 to 5, wherein said

predetermined intensity distribution is an Airy-type intensity distribution.

20

8.   A method as claimed in any of the preceding claims, wherein said

impingement of the beam on said portion is effected in a manner to permit

constructive interference between reflected and non-reflected parts of said beam.

9.   A method as claimed in any of the preceding claims, further comprising effecting relative movement between said portion and the beam after a first cutting operation and thereafter performing a second cut.

10.   A method as claimed in claim 9, wherein said relative movement comprises a small predetermined movement along the longitudinal axis of said fibre or waveguide.

11.   A method as claimed in claim 9 or claim 10, further comprising cutting said portion a third or more time.

12.   An apparatus adapted and arranged to carry out a method as claimed in any of the preceding claims.

13.   An apparatus as claimed in claim 12 comprising:

        means for generating a beam of laser light with a predetermined intensity distribution;

        means for aligning said beam distribution in relation to a portion of an optical fibre or waveguide to permit an amount of said beam exceeding a predetermined level of intensity to impinge on said portion to be cut; and

means for cutting said portion in dependence upon the impingement of said beam on said portion so as to form an optical fibre or waveguide surface of enhanced quality, for example a substantially flat optical surface or a lens of enhanced quality at said portion.

5

14.   An apparatus as claimed in claim 13, wherein said means for generating a beam of laser light is a CO_2 laser operable in the wavelength range between 9.4µm and 10.6µm, preferably in the range between 9.4µm and 9.8µm.

10

15.   An apparatus as claimed in claim 13 or 14 wherein said cutting means is arranged to effect said cutting without relative movement between the laser beam and the fibre or waveguide transverse to the same.

15   16.   A method of cutting a portion of an optical fibre or waveguide with a laser beam, the method comprising:

generating, by means other than focussing, a beam of laser light having a predetermined intensity distribution;

aligning said beam distribution in relation to a portion of an optical

20   fibre or waveguide to permit an amount of said beam exceeding a predetermined level of intensity to impinge on said portion to be cut; and

cutting said portion in dependence upon the impingement of said beam on said portion.

17. A method as claimed in claim 16, wherein said cutting is effected by ablating or vaporising said portion and heating adjacent portions of the fibre or waveguide at a predetermined level.

5

18. A method as claimed in claim 16 or claim 17, wherein the generated beam distribution is formed by imaging.

19. A method as claimed in claim 16 or claim 17, wherein the generated

10 beam distribution is formed by interference.

20. A method as claimed in claim 19, wherein said generated beam distribution is formed by use of an optical interference Lloyd's mirror geometry, or by use of an optical interference Fresnel double mirror

15 geometry, or by use of an optical interference Fresnel Bi-prism geometry, or by use of a Young slits' geometry.

21. A method as claimed in claim 16 or claim 17, wherein the generated beam distribution is formed by diffraction.

20

22. A method as claimed in claim 21, wherein said generated beam distribution is formed by use of mask means.

23.   A method as claimed in claim 22, wherein said mask means comprises a phase mask or zone plate.

24.   A method as claimed in any of claims 21 to 23, wherein said generated beam distribution is formed by use of an echelle grating.

25.   A method as claimed in claim 16 or claim 17, wherein said generated beam distribution is formed by means of optical interference and/or imaging and/or diffraction.

26.   An apparatus adapted and arranged to carry out a method as claimed in any of claims 16 to 25.

27.   An apparatus as claimed in claim 26 comprising:

       means for generating a beam of laser light having a predetermined intensity distribution other than by focussing;

       means for aligning said beam distribution in relation to a portion of an optical fibre or waveguide to permit an amount of said beam exceeding a predetermined level of intensity to impinge on said portion to be cut; and

       means for cutting said portion in dependence upon the impingement of said beam on said portion.

28.   An apparatus as claimed in claim 27, wherein said means for generating a beam of laser light is a CO_2 laser.

29.   A method as claimed in claim 16 wherein cutting of the optical fibre
5   or waveguide is effected without translation of the laser beam across the fibre or waveguide.

30.   A method of cutting a portion of an optical fibre or waveguide with a laser beam, the method comprising:
10   generating a beam of laser light with a predetermined intensity distribution,

aligning said beam distribution in relation to a portion of an optical fibre or waveguide to permit an amount of said beam exceeding a predetermined level of intensity to impinge on said portion to be cut; and
15   cutting said portion in dependence upon the impingement of said beam on said portion so as to form a substantially flat optical fibre or waveguide surface.

Typically 125μm outside diameter

Typically 10μm core diameter

Reflected

Transmitted

Cladding

Figure 1

Laser   Fibre clamp

Fibre

Conventional Geometry

(a)

Fibre clamp

Fibre

Laser   Vertical Laser Geometry

(b)

Laser   Lens   Fibre

(c)

Figure 2

Flared end to fibre

(a)

(b)

Figure 3

Region of Diffused core

Figure 4

Figure 5

Laser

Cut 11

Workpiece movement

10

Figure 6

Conventional line-focus optics

First line focus 17

Region of highest intensity

Second line focus 18

16

15

Figure 7(a)

Single high- intensity line focus

Cylindrical Telescope 20

22

25
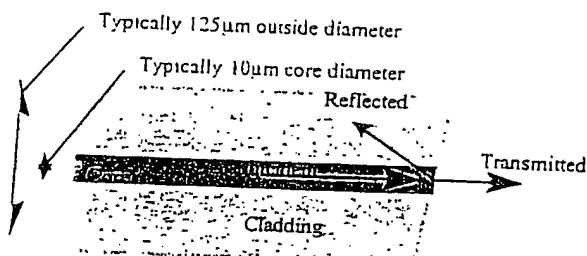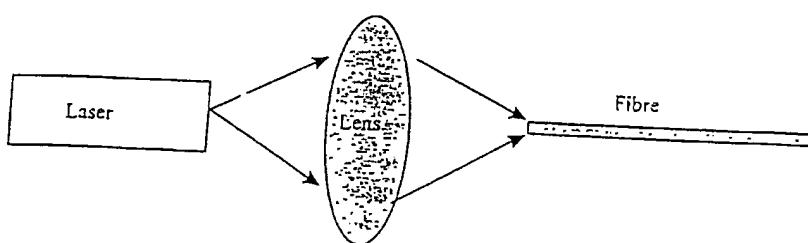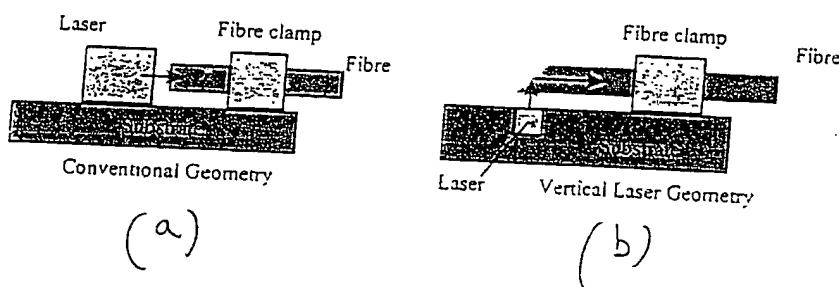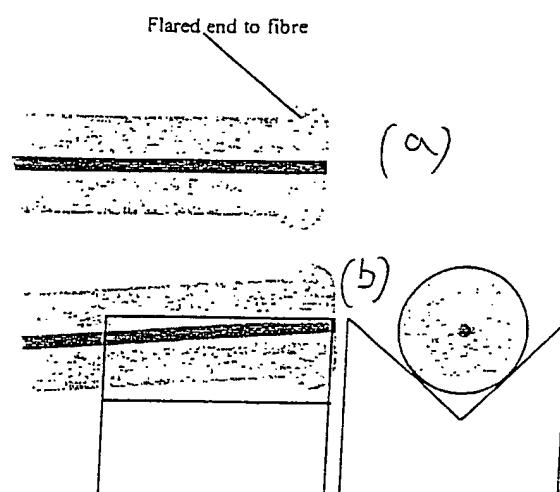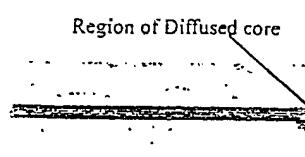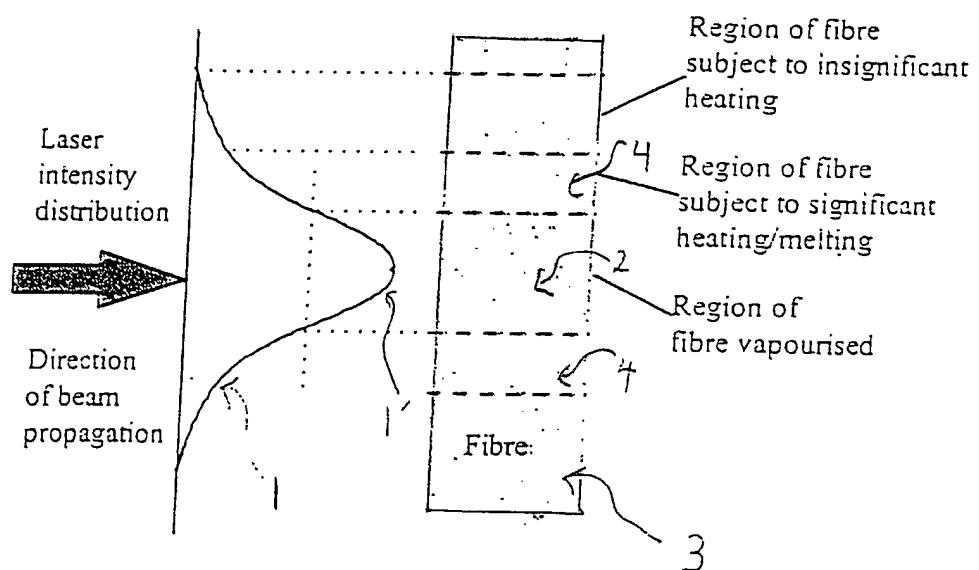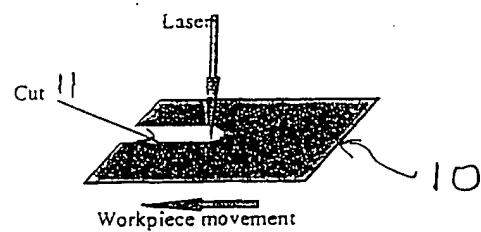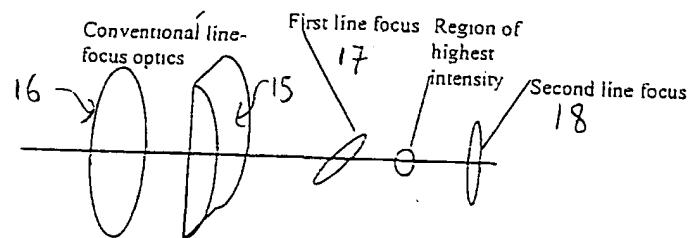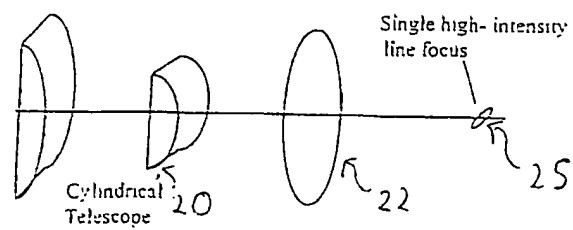
Figure 7(b)

Figure 8

Figure 9

Incoming laser beam

Refected
laser beam

Region of overlapp
& constructive interference

Fibre

Partial cut in fibre

Figure 10 (a)

Incoming
laser beam

Region of overlap
& constructive interference

Transmitted
beam

Refected
laser beam

Figure 10 (b)

Significant
deposited
energy &
hence thermal
effects

35

36

Fibre

37

Vast majority of
beam passes by
end face of fibre

Subsequent
cuts

Cut 1

Figure 11(a)

Laser beam
propagation
Laser into paper

(Top Schematic)

Significant
deposited
energy &
hence thermal
effects

35'

36'

Fibre

37'

Vast majority of
beam passes by
Subsequent   end face of fibre
cuts

Cut 1   (Bottom Schematic)

Figure 11 (b)

Figure 12

Figure 13
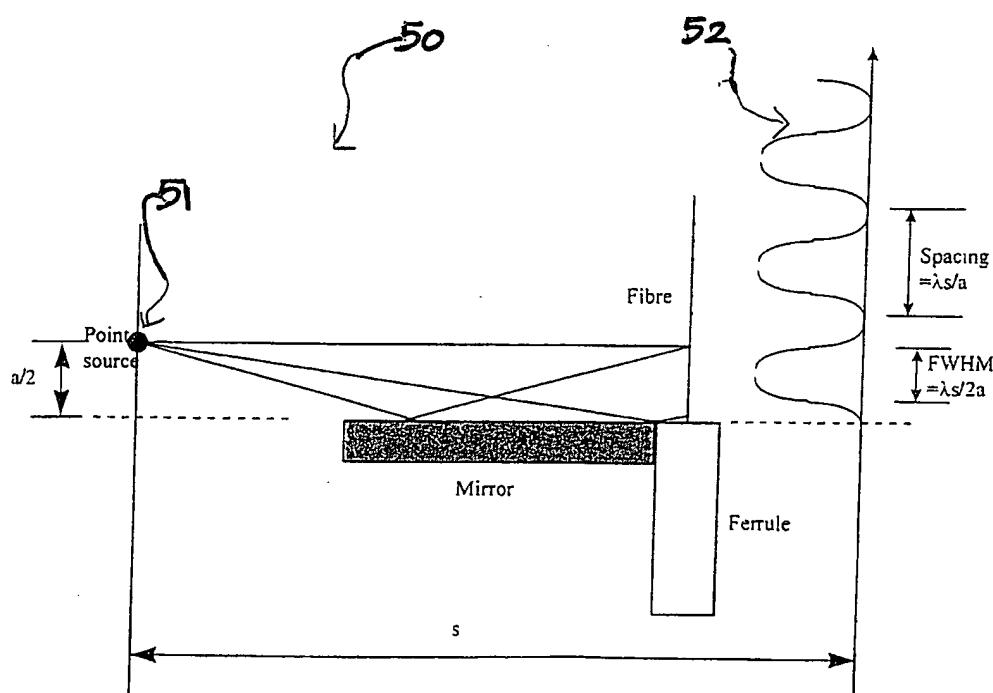
Figure 14

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   B23K26/073

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)   IPC 7   B23K
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Electronic data base consulted during the International search (name of data base and, where practical, search terms used)   EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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-/--

| [X] | Further documents are listed in the continuation of box C. | [X] | Patent family members are listed in annex. |

° Special categories of cited documents .

'A' document defining the general state of the art which is not considered to be of particular relevance

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'O' document referring to an oral disclosure, use, exhibition or other means

'P' document published prior to the International filing date but later than the priority date claimed

'T' later document published after the International filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

'X' document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

'Y' document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

'&' document member of the same patent family

Date of the actual completion of the International search 4 March 2002	Date of mailing of the International search report 18/03/2002
Name and mailing address of the ISA European Patent Office, P B 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Authorized officer De Backer, T

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